A method of studying thermochemical conversion of single biomass particles in an intense air flow

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Abstract. There are many methods for obtaining kinetic data of thermochemical conversion of fuel particles. These methods to some extent reproduce the conditions of industrial processes. At the same time, there is a lack of methods reproducing the conditions of wood particles gasification in downdraft gasifier. In this process, raw fuel enters the hot reactor region with intense air jets blowing through the tuyeres. It is difficult to directly measure the weight of particles under these conditions due to the effect of gas flow. The authors proposed a research method in accordance with which the sample is introduced into a heated furnace and placed in the tuyere flow. The sample is combusted for a certain time then removed from the furnace and quickly quenched. The method allows reproducing the dynamics of changes in temperature, mass, volume, shape and structure of the inner layers of particles. It provides visual observations of the process, high heating rate of wood samples (750-5500 °C min^{-1}) and large amount of data sufficient for statistical processing.

1. Introduction

Most current studies of the solid fuels thermochemical conversion combine methods of physical and numerical experiments. The modeling of these processes uses kinetic data obtained by various methods. One of the common methods is thermal analysis, for which a wide range of industrial equipment has been developed [1]. Often conditions of widely used thermal analysis techniques are far from the conditions of fuel conversion in power plants. This method is characterized by relatively low heating rates of the samples, which are 50–200 °C min^{-1} and only rarely reach 900 °C min^{-1} [2]. The use of crucibles and sample holders causes limitations on heat and mass transfer between the sample and gas [3, 4].

A number of special research methods have been developed in which the conditions of sample conversion are close to industrial. Among them are the methods of combustion particles in the drop-tube furnace [5, 6]. There are methods for studying the conversion of single particles on the surface and inside the fluidized bed [7, 8, 9]. Some articles are devoted to conversion of the samples, which are fixed relative to the gas flow [10, 11]. In most of these methods, modern optical approaches combined with mathematical modeling are used to determine temperature, size, shape and even mass of particles [12, 13]. These methods better reproduce industrial conditions of fuel conversion, and kinetic data obtained with their use can significantly differ from the thermal analysis data [14].

The aim of the study is to develop a method for reproducing the process of wood particles gasification in the space near the tuyeres of the downdraft gasifier. This process is characterized in that the raw fuel is supplied to the tuyeres area. The air flow velocity in the tuyeres can reach tens of meters per second. Direct measurement of the particle weight under these conditions is complicated by

significant forces acting on the sample from the gas flow. There is information about the direct measurement of weight of large wood pieces during their pyrolysis and the gas velocity of 3-15 m s-1 [15]. However, the authors note that the weight of the pieces always exceeded the force of the gas flow. When tuyere is blowing into small particles, this condition is often disturbed and an indirect method is required to measure the weight of the particles.

2. Method of studying the conversion of single fuel particles

2.1. The principle of the method

The proposed method uses many wood particles with similar initial characteristics, such as mass, shape, and size. Each sample is placed in the reactor for a certain period of time and then quickly removed and cooled. Thus, it is possible to obtain samples with different degrees of thermal conversion and measure their mass and other characteristics before and after the experiment. Such an approach makes it possible to reproduce a change in various characteristics of particles on time.

A similar approach was used by F. Scala to study the combustion of coke in a fluidized bed [16]. However, in this approach the same sample was periodically placed into the reactor, cooled in an inert gas and removed from it. The sample was weighed and measured after removal. Then it was again placed in the reactor and continued burning.

2.2. Experimental rig

Figure 1 shows the scheme of the experimental rig for combustion of single particles. The rig consists of a muffle furnace in which the tube for supplying air to the sample is placed. The tuyere is located at the end of this tube. The tube was equipped with a water-cooled jacket and insulated (not shown in figure 1). This allows the air temperature to remain unchanged during the experiment.

A channel is drilled in the center of the particle. Then the particle is mounted on a thermocouple. Such a thermocouple performs both a temperature sensor and a sample holder. The thermocouple is attached to a carriage whose movements are controlled by a servo motor. This system allows us to accurately position the sample in the furnace and adjust the speed of its movement.

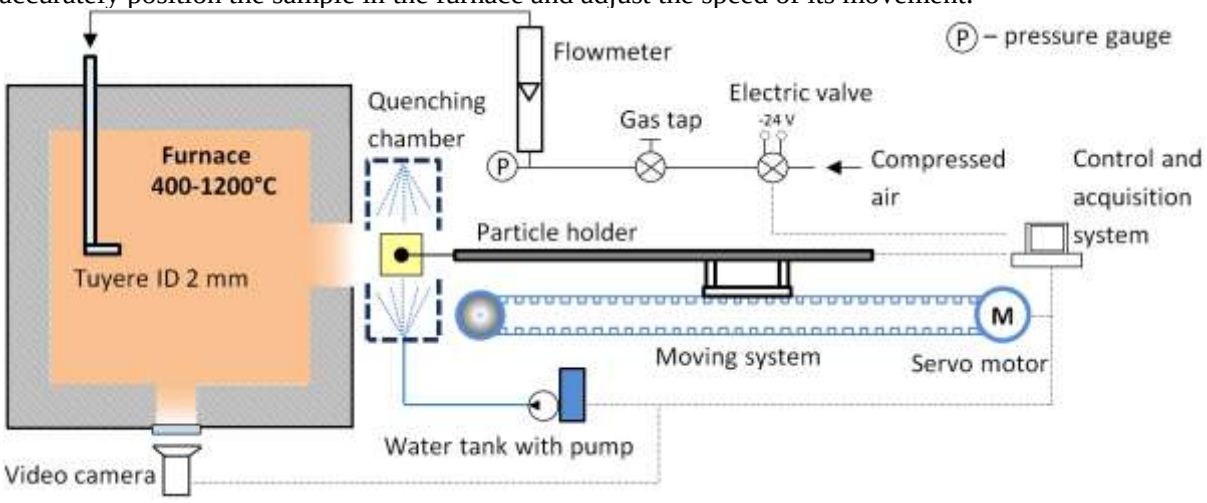

Figure 1. The layout of the experimental rig.

The following rig order is used. A wood sample is placed on the holder at first. Then the air supply is turned on and the particle is placed into the furnace. After a certain burning time, the sample is removed from the furnace and is quenched with water in a quenching chamber. Air supply is turned off immediately after sample removal. The burning process is recorded on the video camera. The control of the rig parts, synchronization of their work and data collection is carried out by the control and acquisition system built on the basis of Arduino board.

Drying of the samples and their subsequent weighing and size measurement is performed after the experiment. There is also the possibility to cut each of the particles and study the structure of their

inner layers. It is possible to grind samples entirely or take part of the charred layer for further ultimate analysis. Such analysis allows one to obtain the time change of elemental composition of the samples.

2.3. Properties of wood samples and experimental parameters

Pine wood was used as fuel. The particles had a cubic shape and were prepared from a single piece of wood. Precise cutting made it possible to obtain particles with side length of 12 ± 0.1 mm. The generalized properties of the samples are given in table 1.

Table 1. Properties of wood biomass.

Mass, mg	Volume, ml	Density, mg ml^{-1}	MC, % ar[a]	Ash, % db	VM, % db[b]
671±11	1.72±0.005	390±6.7	7.5	0.2	84.5

[a] Moisture content, ar – as received.

[b] Volatile matter, db – dry basis.

Only the residence time in the furnace was changed for each of the samples and other parameters remained constant. The furnace temperature was 800 °C, the air velocity in the tuyere was 20 m s-1 and the distance from the tuyere to the sample edge was 20 mm. The whole period of particle combustion was divided into 10 time intervals, namely 2.5 seconds and from 6 to 54 seconds in 6 seconds increments. Five parallel samples were tested for each time interval. The same number of samples was completely burnt in the furnace without removing their residues.

The relative mass of char residue (mr) was calculated on the dry ash-free state according to the equation:

$$m_r = \frac{m_a}{m_{a,0}} 100, \% \quad (1)$$

where m_a and $m_{a,0}$ are the absolute mass value of the charred and initial samples respectively.

3. Results and discussion

3.1. Main regularities of the process

The whole combustion process of a particle can be divided into separate stages (Table 2). The stages of placing and removing samples from the furnace are transitional. The movement speed of the holder is rather high, but below the limit at which the particles fall from the holder as it moves. The heating of the particle started from the moment of entry into the furnace and ended before its corners began to char. Charring of the particle without ignition of volatile followed after the heating step. Some samples were placed in the furnace for 2.5 seconds to study this stage in detail. The average particle mass (m_r) was 96% at the end of the charring stage.

Table 2. Characteristics of individual combustion stages.

Stage	Placing / removing	Heating	Charring	Volatile burning	Char burning
Duration, s	0.28	0.27	2.26	43.2	10.8
m_r, %	100	≈ 100	96	6	n.d.

The stages of burning of volatile and char residue were partially overlapped. Separation of these stages was carried out by disappearance of yellow glow of flame. The yield of carbon residue is 15.3% according to the standard method (Table 1). But the yield of the residue is only 6% at the end of the volatile burning stage. Such a deviation of yields is due to the stages overlapping.

Figure 2a shows the change in the average temperature of the particles that were in the reactor at different times. The sharp drop of temperature is associated with the water quenching of particles. The cooling of particles takes some time and the temperature in the center of the samples continues to grow for 0.5-1.6 seconds after the start of their irrigation with water. This effect is probably associated

with the formation of water vapor in the first moments of the sample quenching. Steam has high thermal conductivity and contributes to the heating of the particle center when it penetrates deep into the particle through the pores. Undesirable secondary reactions of pyrolysis and steam gasification can take place during the quenching of samples. This feature is a disadvantage of the proposed method which reproduces the change in mass of particles.

The rate of particles heating reaches 950 °C min-1 after their ignition. This rate decreases to 750 °C min-1 as the combustion char residue stage starts (figure 2b). The char combustion is accompanied by a significant increase in the heating rate of particles, which reaches 5500 °C min-1. This feature can be used to identify a change in the stage of combustion instead of visual observation of the yellow volatile flame disappearance.

The particle is located on the holder in such a way that the air flow presses the sample to the thermocouple junction (figure 1). This technique allows us to remove samples from the furnace with a high degree of conversion, when the mass of the residue is only 1.7-2.7% of the initial one.

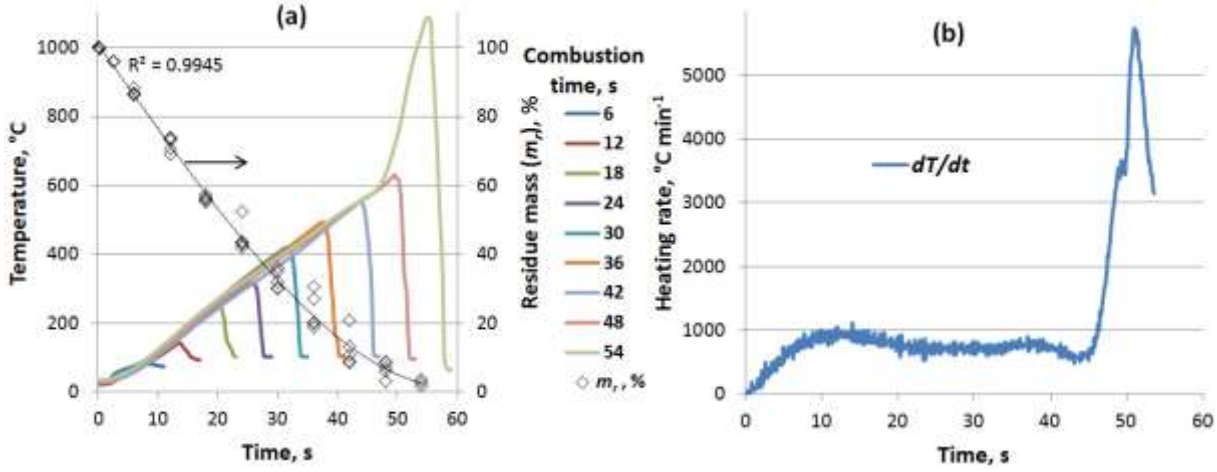

Figure 2. The dependence of average temperature, relative mass of samples (a) and their heating rates (b) on time.

3.2. The possibility of reducing the number of samples

We have tested 55 samples for one mode of the rig. These samples were in the furnace during different times. If a large number of parameters are changed in experiments, then the number of single runs will be in the hundreds. Although the rig is automated, experiments with a large number of samples can become very time consuming. Therefore, it is necessary to determine the minimum possible number of parallel samples and time intervals required to study one mode.

Several reduced sets of experimental data on sample weights were created from the base set. The coefficients of the third degree polynomial (equation (2)) were calculated for each data set.

$$m_r = at^3 + bt^2 + ct + d \text{ , \%} \tag{2}$$

This calculation was carried out by the least squares method. The arrays of the mr points were then calculated for the base and each of the reduced polynomials. Further, the absolute deviation was estimated for these arrays:

$$\Delta m_r = \left| m_{r,base} - m_{r,case} \right| \text{ , \%} \tag{3}$$

Several cases were tested with a reduced amount of data (Table 3). Reducing the number of time points by half or reducing parallel measurements from five to three does not lead to a significant divergence of the dependencies mr = f (t) as compared to the base case. The maximum absolute deviation of the residues mass calculated by polynomials does not exceed 0.7–0.9 percentage points (Table 3). It is possible to reduce the number of samples to 15, but the difference in mass of the residues of case No. 6 and the base case may increase.

The experimental data of the base case are redundant. The function mr = f (t) is monotonously decreasing and it is possible to reduce parallel samples and time points when calculating its coefficients.

Table 3. Cases of reducing the number of samples.

No.	Case[a]	Maximum Δm_r	Number of samples
1	Base, time (all) & parallel points (all)	n.a.	55
2	time (0,12,24,36,48) & parallel points (all)	0.9	25
3	time (0,12,30,42,54) & parallel points (all)	0.7	25
4	time (all) & parallel points (1,3,5)	0.9	30
5	time (all) & parallel points (2,3,4)	0.8	30
6	time (0,12,30,42,54) & parallel points (1,3,5)	1.6	15

[a] The data that was taken for analysis by time and parallel sample number is indicated.

4. Conclusions

We have tested a method that allows reproducing the conditions of particle conversion in the downdraft gasifier. A distinctive feature of the proposed method is to obtain a sufficiently large amount of synchronized data. These data may include changes in the mass, volume and shape of the samples, thermocouple measurements in the particle center, the structure of the particle inner layers, visual observations of the process features, as well as the elemental composition of sample residues and their parts.

The method is quite laborious, despite the fact that the number of samples can be reduced to 15 per mode of the rig. Based on visual observations of the process, it makes sense to increase the number of experiments around the moments of ignition, change of stage and end of sample combustion.

Further improvement of the method can be carried out in several ways. Sample can be placed in a wire basket to avoid loss of residue. This approach will allow to almost burn the sample and remove it from the reactor. It makes sense to consider alternative ways to quench the sample to prevent secondary reactions. For example, it is possible to quench the residue with cold nitrogen produced by the evaporation of a liquid gas. The method involves the removing of samples from the furnace after a certain period of time. In addition it is possible to remove samples by event. For example, when volatile ignites or particle defragmentation occurs.

Acknowledgments

The reported study was funded by RFBR according to the research project № 18-38-00774.

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